

Leptoquark models and the energy spectrum of cosmic rays

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Abstract. The IceCube Neutrino Observatory has recently placed a new limit on the extremely-high energy (EHE) neutrino flux lower than the Greisen–Zatsepin–Kuzmin (GZK) cosmogenic neutrino intensities expected in the case of proton-dominated primary composition. This result favors the mixed chemical composition models and excludes scenarios with strongly interacting neutrinos proposed so far. Nevertheless we argue that it is possible to construct such models consistently with the IceCube data if to extend the standard model Lagrangian by adding a leptoquark term. It is notable that the resulting Lagrangian couples leptons (not only neutrinos!) to gluons through leptoquark excitations in the subprocess $lg \rightarrow lq\bar{q}$ so that leptons of relevant energies in the Earth as well as in Extensive Air Showers will behave as hadrons. The latter may lead, for example, to misinterpretations in identifying the chemical composition of EHE cosmic rays. The EHE primaries will seem heavier due to production of secondary strongly interacting leptons in agreement with the recent observations. We argue that our model naturally predicts many exotic phenomena such as the second knee, centauros, excess of high energy muons (≥ 10 TeV), existence of TeV photons, alignment, penetrating cascades. We also argue that a clear manifestation of physics beyond the standard model has been observed by the IceCube Neutrino Observatory.

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1 Introduction

A really intriguing situation can be observed today in the physics of Extremely High Energy Cosmic Rays (EHECR). During many years of observations a great amount of experimental information has been collected. A lot of different models have been proposed (for reviews see, for example, [1]). From one hand side the existence of the beautiful effect – the Greisen–Zatsepin–Kuzmin (GZK) cutoff [2, 3] – is confirmed experimentally, from the other hand there are indications that the EHECR chemical composition is rather heavier nuclei than protons as recently identified by the Pierre Auger Observatory [4]. An opposite picture is observed by the HiRes which indicates a proton composition [5]. There are also the so-called exotic events whose nature is still unknown [6, 7].

From the existence of the Greisen–Zatsepin–Kuzmin (GZK) cutoff one has to unavoidably deduce that there should be a bulk of neutrinos (referred to as cosmogenic GZK neutrinos) concentrated around the threshold of the following reaction [8, 9]:

$$p\gamma \rightarrow \Delta^+ \rightarrow p\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\nu_\mu\bar{\nu}_\mu. \quad (1)$$

In the laboratory frame the threshold is equal about 5×10^{19} eV.

It was also realized that cosmic rays beyond the GZK cutoff may also exist if they are initiated, for example, by

neutrinos [10]. Models based on the idea (primary neutrinos) have been proposed. For example the so-called strongly interacting neutrino models describe the experimental results very convincingly and seem to be rational provided the cross section of neutrino interactions with matter grows up to values of the order of 1 mb at such extremely high energies (10^{18} eV and above). This is much higher than the standard model predictions.

The IceCube Neutrino Observatory has recently placed a new limit on the extremely-high energy (EHE) neutrino flux lower than the GZK cosmogenic neutrino intensities expected in the case of proton-dominated EHE cosmic rays [11, 12]. This result excludes models beyond the standard model proposed so far.

2 Involving leptons in strong interactions

We stress that the following two states are taken as principles:

- (i) The GZK cutoff exists for protons.
- (ii) The primary EHECR are protons.

Models with strongly interacting neutrinos provide a rational explanation of the shape of the cosmic ray spectrum above 10^{18} eV. They suppose that the GZK cosmogenic neutrinos initiate extensive air showers, just as hadrons and the observed spectrum is nothing but a superposition of two components initiated by the primary GZK neutrinos and protons respectively (see, for example,

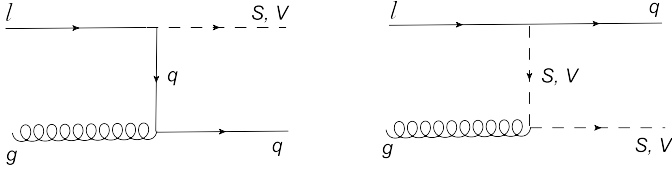


Fig. 1. Lepton–gluon interaction through leptoquark excitation (S – skalar and V – vector leptoquarks)

[13]). All such models proposed so far have been convincingly excluded by the IceCube Neutrino Observatory.

How to consistently involve leptons in strong interactions? We propose here a method using a leptoquark Lagrangian. The existence of leptoquarks was predicted by W. Buchmüller, R. Rückl and D. Wyler in 1986 [14].

Let us extend the standard model Lagrangian (\mathcal{L}_{SM}) by adding a leptoquark term (\mathcal{L}_{LQ})

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{LQ}. \quad (2)$$

The general $SU(3) \times SU(2) \times U(1)$ invariant Lagrangian that couples neutrinos to leptoquarks has the form [14]:

$$\begin{aligned} \mathcal{L}_{LQ} = & g_1 \bar{q}_L^c i \tau_2 \ell_L S_1 + g_3 \bar{q}_L^c i \tau_2 \tau \ell_L \mathbf{S}_3 \\ & + g_2 \bar{d}_R^c \gamma^\mu \ell_L V_{2\mu} + \tilde{g}_2 \bar{u}_R^c \gamma^\mu \ell_L \tilde{V}_{2\mu} + \tilde{h}_2 \bar{d}_R \ell_L \tilde{R}_2 \\ & + h_2 \bar{u}_R \ell_L R_2 + h_1 \bar{q}_L \gamma^\mu \ell_L U_{1\mu} + h_3 \bar{q}_L \tau \gamma^\mu \ell_L \mathbf{U}_{3\mu} \\ & + h.c. \end{aligned} \quad (3)$$

The Lagrangian (3) contains eight scalar and vector leptoquarks per family grouped into weak isospin doublets or triplets (indicated by indexes 1 – singlet, 2 – doublet, 3 – triplet) and couples leptons to gluons through leptoquark excitations as shown in Fig. 1.

Therefore one can calculate the corresponding cross sections of the following reactions:

$$lg \rightarrow qL, \quad (4)$$

where l are leptons (ν_i, l_i^-), g – gluons, L – leptoquarks. The leptoquarks subsequently decay into a lepton–quark pairs so we have the following subprocesses:

$$l_i g \rightarrow qL \rightarrow q\bar{q}l_j, \quad (5)$$

The advantage of this model in comparison with other ones proposed so far is the fact that not only neutrinos but also charged leptons interact strongly at the appropriate energies, probably near the leptoquark pole (resonance production).

The final step is to convolute the cross sections with gluon densities of the nucleon.

It is enough to show that within this model one can obtain lepton–nucleon cross sections of the order of 10 mb to be in agreement with observations of EHECR.

To demonstrate how this model works, let us consider the excitation of the vector leptoquark from the singlet, i.e., consider the effective Lagrangian:

$$\mathcal{L}_{eff} = h_1 \bar{q}_L \gamma^\mu \ell_L U_{1\mu} \quad (6)$$

In the leading order we have obtained the following cross section:

$$\sigma(s) = \frac{4\alpha_s \lambda}{3M_L^2} \left[f_1(y) + f_2(y) \ln \frac{M_L^2(y-1)^2}{m_q^2 y} \right], \quad (7)$$

where

$$f_1(y) = 2\left(1 - \frac{1}{y}\right)\left(1 + \frac{2}{y^2} - \frac{1}{y^2} \ln y\right),$$

$$f_2(y) = \frac{1}{y}\left(1 - \frac{2}{y} + \frac{2}{y^2}\right),$$

M_L and m_q are masses of the leptoquark and the quark, α_s – the strong coupling constant, $y = s/M_L^2$, s – the center of mass energy, λ – a constant corresponding to $l - L - q$ vertex. Our model contains two parameters beyond the standard model: λ and M_L .

Now we convolute the cross section (7) with the gluon distribution of the nucleon:

$$\sigma(E) = \int_{x_0}^1 \sigma(xs) g(x, s) dx, \quad (8)$$

where E is the incident lepton energy in the laboratory frame. We choose a usual parameterization of the gluon distribution:

$$g(x, s) = \frac{(1-x)^m}{x^n}. \quad (9)$$

We have taken $m=5$, $n=1.5$, $\alpha_s = 0.1$, $\lambda=1$, $M=500$ GeV and performed calculations for two values of m_q : $m_q = 0.2$ GeV and $m_q = 1$ GeV, $x_0 = M^2/As$, A – is the mass number of the air/earth nucleus which contains the target nucleon (see Fig.2).

It should be noted that the gluon density at such extremely high energy transitions is unknown. One can suppose, for example, that the leptoquark production in lepton–nucleus interactions (in the air or in the Earth) becomes possible due to the gluon density is very high at such a regime. It is also very important that the incident particle is just a lepton for reaching the region of ultra low values of the Bjorken variable. In pp collisions it would be more difficult to probe the same values of x since the condition $M^2 \approx x_1 x_2 s$ takes place.

We emphasize that our numerical calculations must be regarded only as a qualitative demonstration of the model. There are a number of unknown parameters, apart from the leptoquark masses and the constants λ .

Nevertheless the model proposed in this paper has an impressive predictive power for astrophysics. We demonstrate this fact in the next section.

3 Predictions

It is notable that one can make a number of significant predictions without numerical calculations.

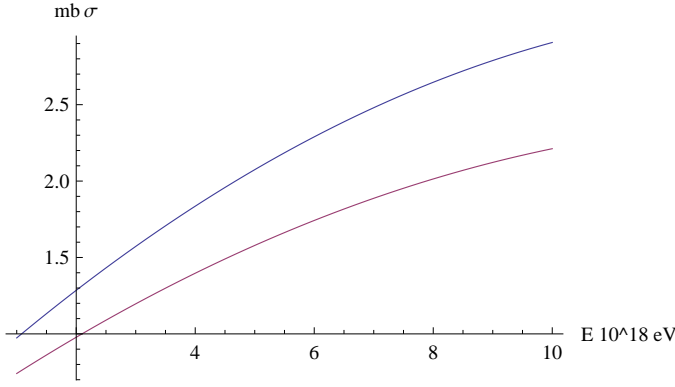


Fig. 2. The leading order cross section of a lepton–nucleon interaction through vector leptoquark excitation v.s. lepton energy in the laboratory frame. Two values of quark masses are considered: $m_q=0.2$ GeV (blue curve) and 1 GeV (red curve), M is taken to be 500 GeV

1) The recent results of the IceCube Neutrino Observatory favor the idea that the EHE leptons interact strongly and therefore may be absorbed in the Earth.

2) Within the proposed model, it is possible to explain the energy spectrum of EHECR as a superposition of two components initiated by the primary GZK neutrinos and protons respectively.

3) The EHE primaries will seem heavier due to production of secondary strongly interacting leptons. For example some muons may be misidentified as hadrons.

4) The TeV photons may be explained as bremsstrahlung of EHE charged leptons (say electrons) produced in the first interactions high in the atmosphere.

5) Centauros, excess of high energy muons (≥ 10 TeV), penetrating cascades seem not to be so exotic in the model of strongly interacting leptons and can be easily explained. For example, the probability that the neutrinos with energies out of the leptoquark pole can penetrate deeply in the atmosphere and then interact strongly is not equal to zero. Centauros seem to be nothing but leptons misidentified as hadrons.

6) The alignment may exist due to leptoquark decays $L \rightarrow ql$ (only one hadronizing quark in the final state).

7) The events observed above the GZK cutoff and debated so far may be interpreted as induced by neutrino primaries.

8) The IceCube data favor the assumption that all the three families of leptoquarks exist since no EHE tau lepton has been observed.

9) The masses of leptoquarks are of the order of 1 TeV.

In conclusion we would like to note that all the arguments given in this section suggest that we deal with physics beyond the standard model and its clear manifestation has been observed by the IceCube Neutrino Observatory.

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